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Invited Paper

Near-field optical data storage: Avenues for Improved Performance

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Abstract

Because they produce small spot size, near-field techniques are applied to optical data storage systems in order to increase recording density. For data storage, the optical near field is defined in terms of evanescent coupling between the system used to read data and the recording layer. Two practical implementations that use evanescent energy are aperture probes and solid immersion lenses (SILs). In this paper, the basic characteristics of these systems are reviewed, and some considerations for improving performance are discussed. Combinations of SILs and apertures could produce data storage systems with ultra-fine resolution and good detection characteristics.

KEY WORDS: optical data storage, near-field optics, solid immersion lens, aperture probes, evanescent energy

1. Introduction

Both solid immersion lens (SIL)[1] systems and aperture[2] systems have been used to record on and retrieve data from optical media. SIL systems are attractive because they produce spots smaller than conventional optical systems and they have high throughput. Aperture systems are attractive because they offer the smallest spot size. In this paper, both systems are reviewed in terms of basic detection properties, and considerations for improving system performance are listed.

A typical arrangement for *near-field* optical recording using a SIL is shown in Figure 1. Light from a laser passes through a beam splitter and is focused onto a recording layer by an objective lens. The recording layer is on a disk that spins under the objective lens. The recording layer contains spiral tracks of mark patterns that differ in reflectivity from the area between marks. As the focused laser beam passes over a mark, the reflected light level changes. Changes in the reflected light level are sensed by using the beam splitter to direct a portion of the reflected light onto a silicon detector. The detector current, which is a representation of the mark pattern, is decoded to produce digital information. The fidelity of the detector signal determines the amount of data per unit length of track that can be decoded with high reliability.

There are several factors that influence the fidelity of the detector signal. The most important factor for closely-spaced marks is the focused *spot size s*. Large s blurs the reflected light signal, resulting in a loss of *contrast V* in the detector signal. Contrast is defined as $V = (I_{MAX} - I_{MIN})/(I_{MAX} + I_{MIN})$, where I_{MAX} and I_{MIN} are shown in Fig. 1. Conversely, if s is small, changes in the reflected signal are sharp as the marks traverse under the spot. Therefore, as s decreases, the contrast and fidelity increase. Increased fidelity and contrast lead to smaller detectable changes in the mark pattern, so smaller marks can be used and more data can be packed into each track. In systems that are limited by media noise, the signal-to-noise ratio is maximized by maximizing contrast.

Unfortunately, s cannot be made arbitrarily small. Due to the physics of diffraction, the minimum

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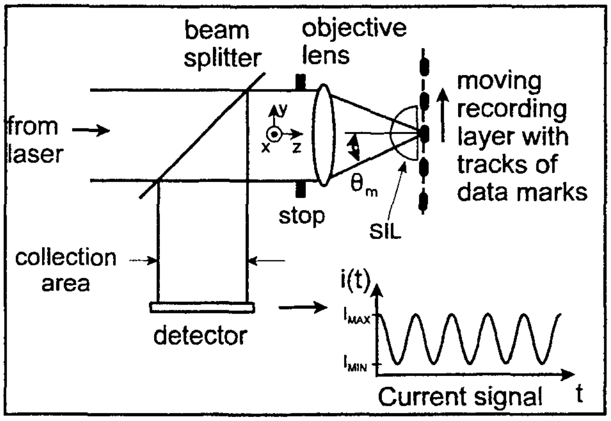

Figure 1. System for near-field recording using a SIL.

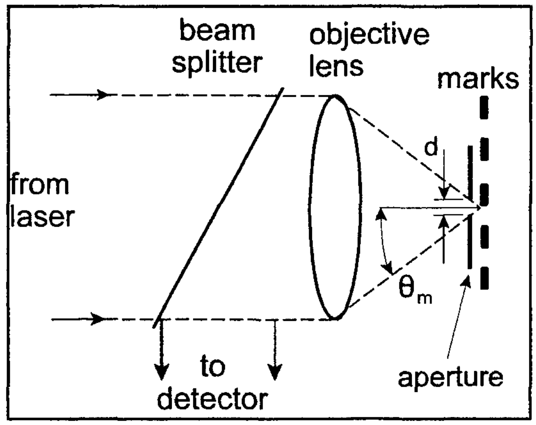

Figure 2. System for near-field recoding using an aperture.

spot size s for SIL systems is a function of the wavelength of the laser λ, the focusing properties of the objective lens, system aberrations, and the thin-film structure used as the recording layer.[3] A simple relationship that is used to estimate the full-width-at-$1/e^2$ spot size for conventional gaussian illumination[4] at the stop is $s = \lambda / (n \sin\theta_m)$, where λ is the wavelength in air, θ_m is the marginal ray angle, and n is the refractive index of the SIL. The marginal ray passes just at the edge of the stop, which is the limiting aperture of the system. The value of $(n \sin\theta_m)$ is the effective numerical aperture NA_{EFF} of the system. As NA_{EFF} increases or λ decreases, the spot size s gets smaller, and mark density can increase. Given that new laser systems will be developed to reduce λ,[5] this paper describes how to increase NA_{EFF}.

A *near-field aperture system* is shown in Figure 2. An aperture of diameter $d < \lambda$ is placed in proximity to the recording layer, and the mark pattern is scanned. The illumination for the aperture can be from a fiber waveguide or a lens. The size of the light spot interacting with the marks is mainly determined by d. The reflected light collected by the objective lens is passed to the detectors, where the current signal is decoded to produce digital information. Like with the SIL system, smaller spots yield higher contrast and greater data density. This simplistic model can also be applied to superresolving systems, like SuperRENS media,[6] as a basic description of the device.

In the following sections, the basic detection principle of both systems is reviewed, and considerations for improved performance are listed. Section 2 briefly reviews how light scatters from near-field interfaces and how light is collected. Section 3 described the evanescent nature of near-field coupling. Section 4 describes how the scattered light produces modulation in the detector signal. Section 5 suggests avenues that may be useful for improving performance of near-field systems, and Section 7 presents conclusions form this work.

2. Scattering and collection of light energy

Light focused into the recording layers and scattered from them may be described in two ways. One way is in the *spatial domain*, where the physical distribution of light energy is determined as a function of the transverse dimensions at an observation plane inside the recording layers, as shown in Fig. 3. The spatial domain is easily understood and is useful to estimate spot size and other parameters. The second way is to describe the energy in the *frequency* (or *angular*) *domain*.[7,3]

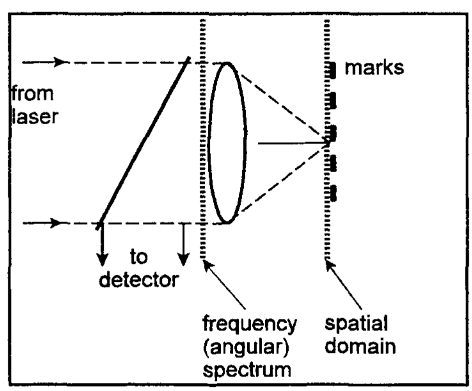

Figure 3. Spatial and Frequency Domains

The angular distribution of the focused spot is found by taking the Fourier transform of the spot amplitude distribution. The angular distribution of the focused spot inside homogeneous recording layers (no marks) is called the *illumination system transfer function* (ISTF), and is useful for understanding the roles of evanescent and propagating energy.(refs: milsters) The angular distribution of the reflected light is important, because it represents the distribution of reflected light collected by the objective lens and incident onto the detector. The reflected light distribution is often nonuniform, and it depends on the mark structure and medium parameters. Angular distributions are functions of direction cosines α and β, which correspond to the x and y axes, respectively, in the spatial domain. The ISTF is denoted by $H(\alpha,\beta; \Delta z)$, where Δz is the distance from the bottom of the near-field coupling surface to the observation plane. α_m is the direction cosine corresponding to the marginal ray angle, $\alpha_m = \sin \theta_m$.

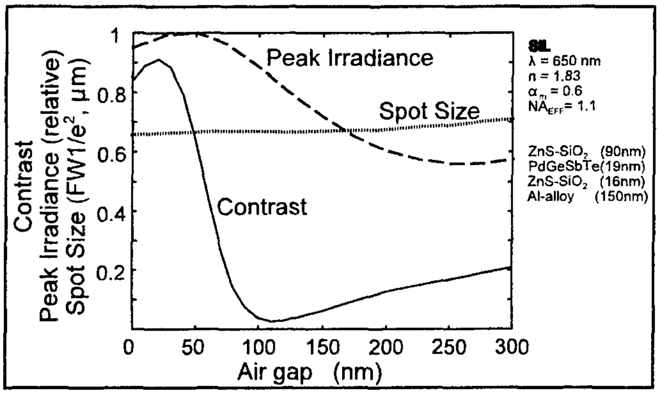

Figure 4. Several important parameters for a particular phase-change medium versus gap height.

The ISTF has also been shown to be a fundamental design tool for analyzing and optimizing SIL systems that use phase-change media.[8] For example, a plot of the peak energy, spot size, and contrast of a particular phase-change media geometry is shown in Fig. 4. For this system, the contrast is a more sensitive function of the gap between the bottom of a SIL and the recording surface than either the spot size or the peak irradiance in the recording layer. Shimura *et al.* in Reference 8 has shown a masking technique based on information obtained from ISTF calculations that improve contrast significantly for this system.

3. Evanescent characteristics of near-field devices

In aperture systems, a hole smaller than s is placed in an otherwise opaque mask near the recording layer. Hole-type apertures can be made with diameters much less than 0.5 μm. The angular specturm contains components that are well outside the range possible with a far field system, that is, without near-field apertures or SILs. For example, consider a 0.25μm diameter aperture illuminated by a λ= 0.5 μm laser beam with a uniform beam profile. The resulting angular spectrum $|H(\alpha,0; \Delta z=0)|$ in air is shown in Fig.5. A dashed line is included to indicate the boundary line where $\alpha_m = 1$. The energy outside the boundary line in Fig. 4 has special properties. It is called *evanescent energy* and does not propagate like the light inside the boundary line, which can be focused and imaged with a far-field system. Evanescent energy decays exponentially as the distance Δz between the aperture and the observation plane increases. The rate of evanescent decay depends on the radius $\rho = (\alpha^2 + \beta^2)^{1/2}$ for $\rho > 1$. A relationship that describes the evanescent decay is

$$|H(\alpha,\beta;\Delta z)| = |H(\alpha,\beta;0)| \exp\left\{-\frac{2\pi}{\lambda}\sqrt{\rho^2-1}\,\Delta z\right\} \quad , \qquad (1)$$

where $|H(\alpha,\beta;\Delta z)|$ is the amplitude of the ISTF for a given Δz. For example, Fig. 6 shows $|H(\alpha,0; 50\text{nm})|$. It is apparent that energy in the range $\rho > 1$ is significantly reduced, even at a distance of only 0.1 λ from the aperture. The resulting spot profile $|h(x,0; 50\text{ nm})|$ is much smoother than the spot profile $|h(x,0; 0)|$ shown in Fig.5, so the detected signal is not as sharp when the hole is away from the data. Therefore, apertures that pass a significant amount of evanescent energy must be used very close to the data layer to gain full advantage of the smaller spot size. The effective numerical aperture for aperture systems is $NA_{EFF} = \lambda/d$, which is the approximate limit to the angular spectrum of the ISTF.

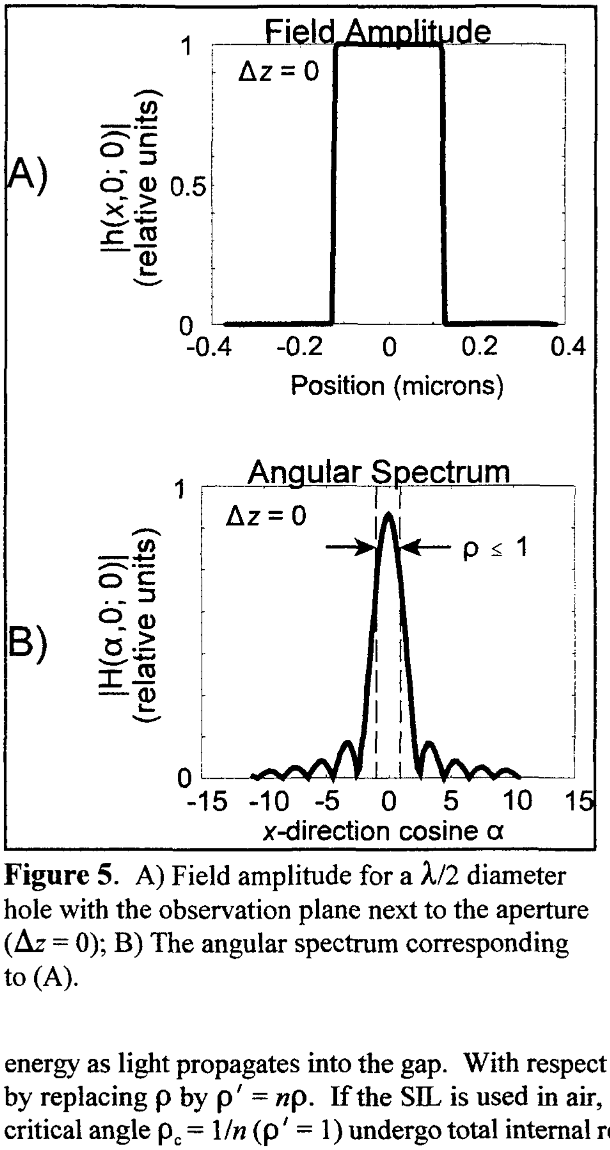

Figure 5. A) Field amplitude for a $\lambda/2$ diameter hole with the observation plane next to the aperture ($\Delta z = 0$); B) The angular spectrum corresponding to (A).

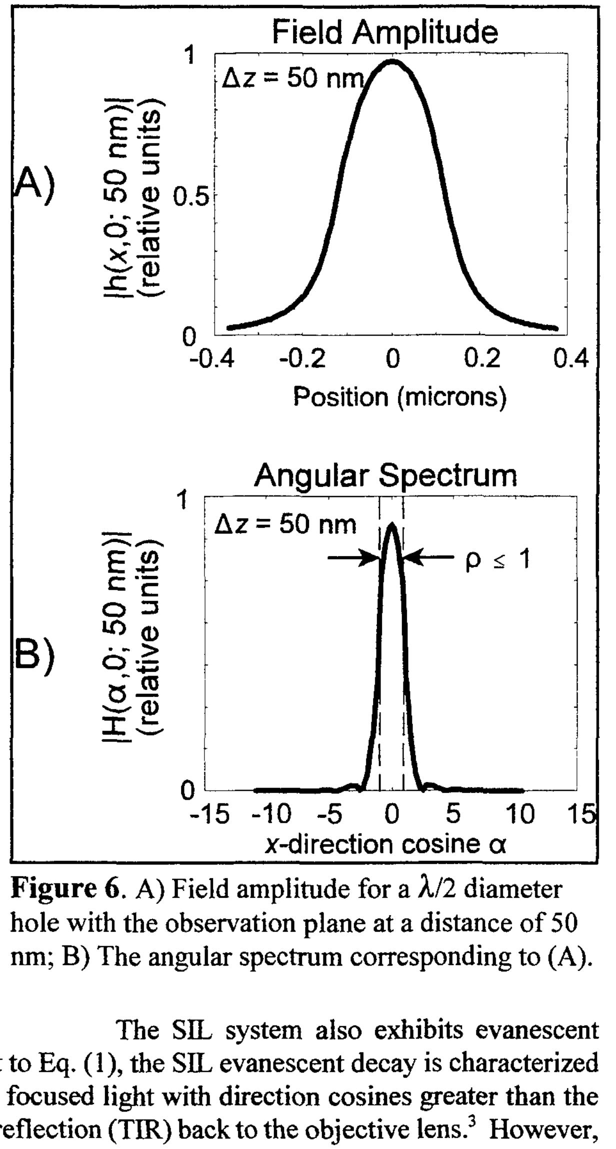

Figure 6. A) Field amplitude for a $\lambda/2$ diameter hole with the observation plane at a distance of 50 nm; B) The angular spectrum corresponding to (A).

The SIL system also exhibits evanescent energy as light propagates into the gap. With respect to Eq. (1), the SIL evanescent decay is characterized by replacing ρ by $\rho' = n\rho$. If the SIL is used in air, focused light with direction cosines greater than the critical angle $\rho_c = 1/n$ ($\rho' = 1$) undergo total internal reflection (TIR) back to the objective lens.[3] However, TIR light passes a short distance past the SIL interface where the light is evanescent, that is, exponentially decaying away from the interface. In fact, the evanescent decay is similar to decay of light from a hole-type aperture.

For both hole-type apertures and SIL systems, the recording layer must be in proximity to the coupling surface. For hole-type apertures, the coupling surface is the aperture. For SILs, the coupling surface is the flat surface of the SIL. Without close proximity, the spot size increases and the total energy available for coupling into the recording layer decreases due to evanescent decay. What differentiates near-field systems from far-field systems is the use of evanescent energy to project small spot sizes into the recording layers. The small spot sizes of near-field systems are otherwise impossible to obtain with far-field systems using the same laser wavelength.

Since a small air gap is present in both aperture systems and SILs, some decay of evanescent energy is always observed. If the energy in the gap has significant components beyond the $\rho = 1$ boundary, even very tiny gap changes can produce significant changes in the light spot. An important observation is that not all of the energy is evanescent. However, as performance is pushed to smaller spot sizes, the amount of evanescent energy increases, and the sensitivity to gap variations is increased.

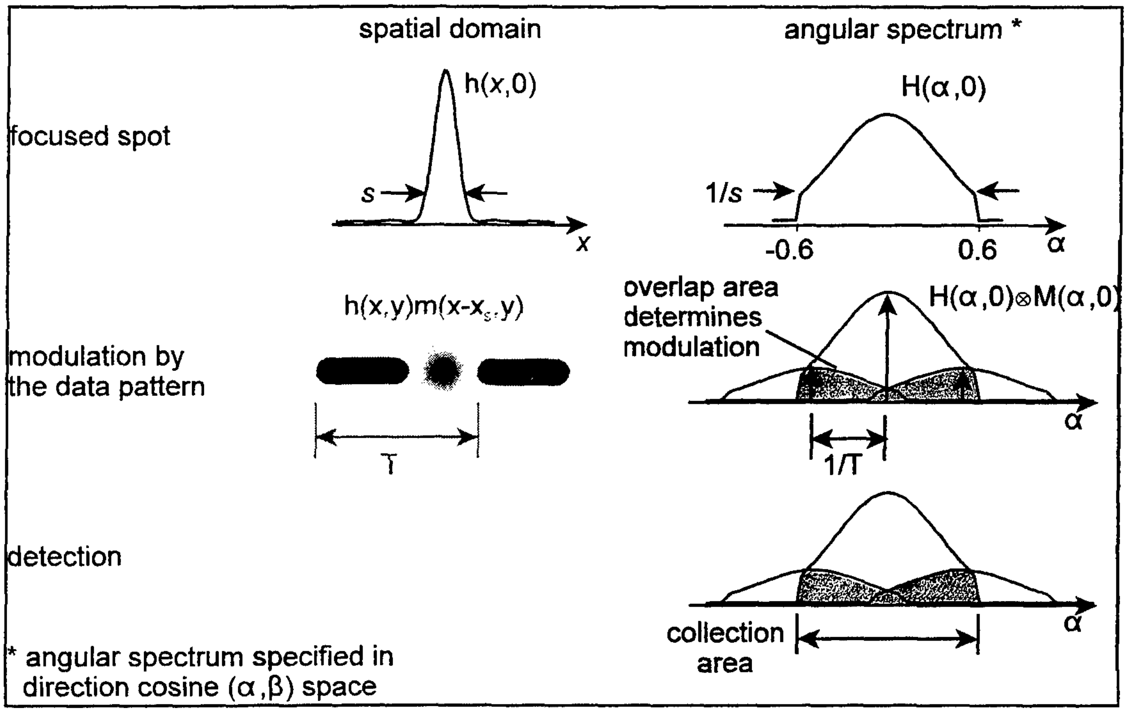

Figure 7. The basic process of detection for a DVD-type system with NA = 0.6.

4. Detection and Modulation

The basic process of detection is illustrated in Fig. 7 for a DVD-type far-field system. The focused spot h(x,y) with size s scans the data pattern m(x,y). The period of the mark pattern is T = 2λ. The reflected light is modulated according to h(x,y)m(x-x_s,y), where x_s represents the scan coordinate of the disk. In frequency space, the Fourier transform of the mark pattern produces diffracted orders that, when convolved with H overlap within the collection area of the objective lens. Each diffracted order spans a range $|\alpha| < 0.6$. As x_s increases, the phases of the diffracted orders change, and the resulting interference with the zero order creates light modulation in the overlap areas. The light modulation produces current modulation in the detectors, which is decoded to provide digital information. The larger the amount of overlap area, the larger the modulation. Large modulation produces high contrast in the detector current.

The modulation behavior of an aperture system and a SIL system scanning a mark pattern. Figure 8(a) displays the angular (frequency) spectrum of a near-field aperture system for d = λ/2 and T = λ. The collection area corresponds to a lens with NA = 0.6.

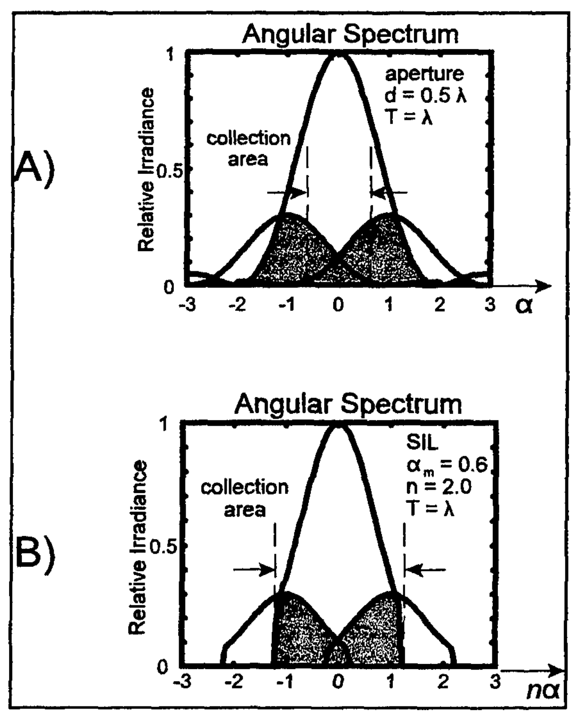

Figure 8. A) Angular spectrum for an aperture system; B) Angular spectrum for a SIL system.

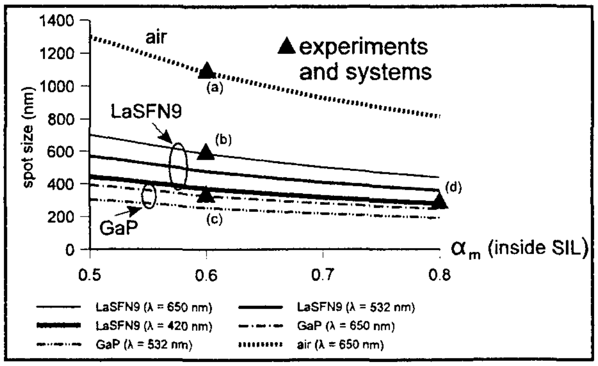

Figure 9. Spot size versus marginal-ray direction cosine (NA) for two SIL materials and three wavelengths. Triangles are experimental results or demonstrations. (a) DVD-type systems; (b) See Reference 8; (c) See Reference 9; (d) See Reference 10.

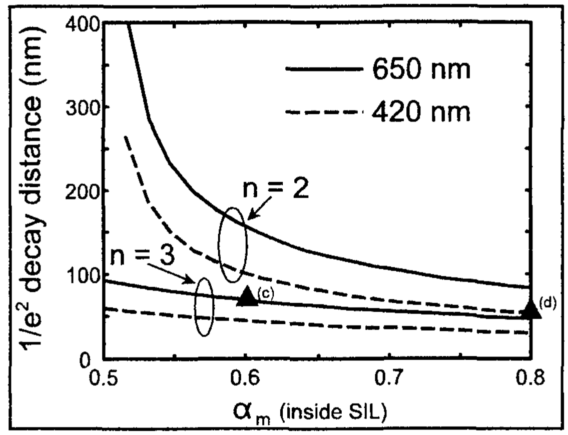

Figure 10. $1/e^2$ decay distance of the marginal-ray evanescent field for two SIL materials and two wavelengths. Triangles refer to experiements as described in Figure 9.

Notice that $NA_{EFF} \sim 2.0$. The overlap area is substantial, so a high contrast current signal should be expected. However, unlike the DVD system, substantial modulation exists outside the collection area. Figure 8(b) displays the angular spectrum of a SIL system for $\alpha_m = 0.6$, $n = 2.0$, $NA_{EFF} = 1.2$, and $T = \lambda$. Like the aperture system, the overlap area is large, and high contrast is expected. The collection area is larger than the aperture system due to the SIL's high index of refraction.

5. Avenues for Improving Performance

A simple calculation based on $s = \lambda/n\alpha_m$ yields the spot-size curves shown in Fig. 9 for SIL systems using LaSFN9 glass or GaP material. The curves are drawn as a function of α_m for three laser wavelengths, 650 nm, 532 nm, and 420 nm. No curve is drawn for GaP material at 420 nm because the material is highly absorbing at that wavelength. The triangles (▲) represent experimental data points or demonstrations. Dramatic improvement in spot size is obtained for all SIL systems. Beyond $\alpha_m = 0.6$, the spot-size reduction is not significantly improved by increasing α_m. The GaP system at a laser wavelength of 650nm exhibits smaller s than the LaSFN9 system at a wavelength of 420 nm for a given value of α_m.

Extending the performance of SIL systems beyond what has been demonstrated may be difficult due to the sensitivity of the gap height due to decay of the evanescent energy. Figure 10 shows the $1/e^2$ decay distance of the marginal ray versus the direction cosine of the marginal ray α_m. For low α_m and long wavelength, the decay length is large, and good tolerances are observed. However, this combination of parameters does not yield good spot size, as shown in Fig. 9. To achieve fine spot size, the wavelength must be short and n must be as high as possible. Figure 10 shows that with a laser wavelength of 420 nm and $n = 2.0$, the $1/e^2$ decay length for the Sony system described in Reference 10 (system (d) in Figure 10) was less than 100 nm, which was the upper limit of the gap height used in the experiment. The system used in Reference 9 (system (c) in Figure 10), which uses a GaP lens and a laser wavelength of 650 nm, has similar tolerances. The optimum operating conditions for these experiments includes operating the SIL at a much lower gap height, say 50 nm or less. Even with today's state-of-the-art equipment, it is difficult to maintain this gap tolerance. With more experience and development, the practical gap height and associated tolerances may be reduced, but, at this time, it does not appear that much improvement is practical. This consideration of the evanescent day is a first-order consideration in the design of SIL systems. However, other considerations, like the signal contrast shown in Fig. 4, may limit the gap height before spot size or evanescent decay is problematic.

Aperture systems are not fundamentally limited by spot-size constraints. Focused-ion beam techniques have proven that apertures can be fabricated in Al and Cr metallic layers down to 50 nm diameter. However, the practical consideration of gap height and power throughput are limiting factors. For example, Figure 11 illustrates the tradeoff between gap height and aperture size with respect to spot size. Small holes with diameters ~ $\lambda/10$ have low throughput and diverge rapidly in the gap. Larger holes with diameter ~ $\lambda/3$ have higher throughput and do not diverge as rapidly. Therefore, the spot size *s* in an observation plane a reasonable distance (~ 30 nm) from the aperture will be smaller for the large hole than for the small hole.

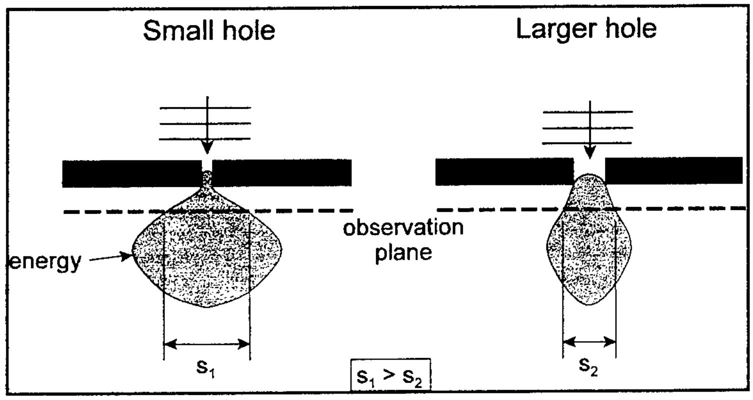

Figure 11. When using apertures to obtain small spot size, the distance to the observation plane is important due to the rapid increase in spot size away from the aperture.

An additional practical consideration is the concentration of thermal energy near the coupling surface. SIL systems that focus light within a few hundred nanometers of the bottom surface of the SIL. The focused light spot creates an intense heat source that can damage material in the gap, like lubricants. The damaged material can produce obstructions to the beam path. One solution to this problem is to provide a high-index cover layer on top of the recording surface a few microns thick. With the coupling layer, the light is slightly defocused in the gap, and the energy density is dramatically reduced. Therefore, the heat is largely removed from the gap region. However, practical difficulties remain with respect to the manufacturing of the protective layers.

Combination of an aperture with a SIL can lead to improved detection. For example, Fig. 12 displays the angular spectra of two aperture systems scanning a mark pattern with T = 0.5λ. Fig 12(a) displays the result for an aperture system, where only a small fraction of the modulation is passed to the collection area. Fig. 12(b) displays the result when a SIL is used in conjunction with the aperture. The amount of overlap area is significantly improved, and a higher contrast signal will result. However, combinations of apertures with SILs presents a significant challenge with respect to the practical aspects of such a device. For example, the focused beam must remain centered over the aperture during recording and playback. On the other hand, the aperture could be used to compensate for some systematic errors, like mild aberrations, caused by component misalignments.

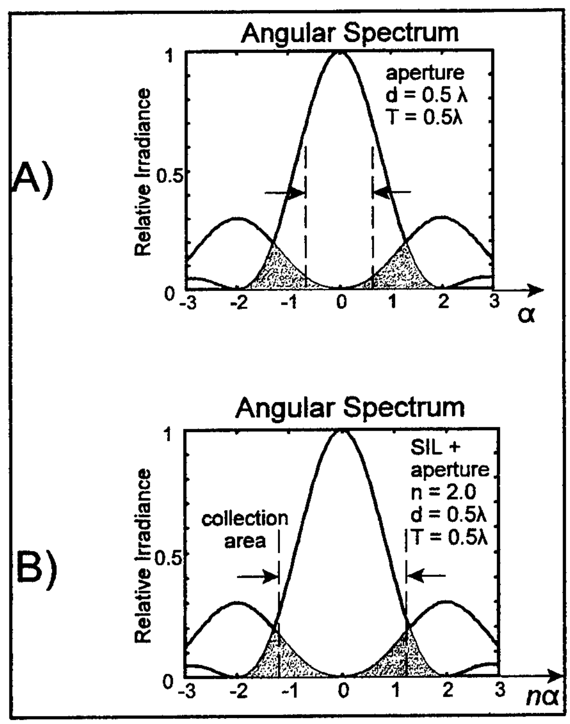

Figure 12. A) Angular spectrum of an aperture system with closely spaced marks; B) Angular spectrum of an aperture + SIL system with closely spaced marks.

The very small aperture laser (VSAL)[11] uses a metallic aperture to form the light spot that interacts with the recording layer, so it suffers the same considerations as other near-field systems with respect to the decay of evanescent energy and contamination of the near-field interface. Therefore, the size of the VSAL aperture is limited as shown in Fig. 11. Too small of an aperture is not practical due to the rapidly increasing spot size. However, the detection process for the VSAL is different than other techniques because detection occurs inside the laser cavity, which is very close to the aperture. In order to get the maximum benefit, the VSAL cavity should be designed to propagate the high spatial frequency components during readout, as shown in Fig. 8(a).

6. Conclusions

The basic detection process of both SILs and apertures is well described using a frequency-space description. Modulation of the detector current is shown to be due to overlap of diffracted orders in frequency space. As the marks become more closely spaced, the diffracted orders move farther apart, and the overlap area decreases. Near-field systems make use of evanescent energy in the gap that is represented in frequency space where $\rho > 1$. Frequency components in the evanescent region decay exponentially as the gap increases. The contrast of the readout signal is shown to be more sensitive to gap variations than the spot size or peak irradiance when SILs are used with a phase-change media structure.

The performance of near-field systems can be improved to give smaller spot sizes. For SILs, the implementation of both high index SILs with red wavelength and lower index SILs with blue wavelengths have been shown. However, these systems use a very small gap (~ 50 nm) that may be near the practical limit. Aperture systems with very small holes can only be used with the medium impractically close to the aperture. Instead, slightly wider holes can be used to give small spot sizes with reasonable gap heights. The combination of a SIL lens and an aperture probe during readout can greatly improve the detectability. and contrast of the data signal.

7.0 Acknowledgments

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8. References

1. S. M. Mansfield, W. R. Studenmund, G. S. Kino and K. Osato, "High numerical-aperture lens system for optical data storage," *Opt. Lett.* **18** (4), 305-307 (1993).
2. E. Betzig, J. K.Trautman, R. Wolfe, E. M. Gyorgy, P. L. Finn, M. H. Kryder, and C-H. Chang, "Near-field magneto-optics and high density data storage," *Appl. Phys. Lett.*, **61** (2) 142-144 (1992).
3. T. D. Milster, J. S. Jo, and K. Hirota, "Roles of propagating and evanescent waves in solid immersion lens systems," *Appl. Opt.*, **38** (23), 5046-5057 (1999).
4. H. M. Haskal, "Laser recording with truncated Gaussian beams," *Appl. Opt.* 18(13), pp. 2143-2146 (1979).
5. S. Nakamura, M. Senoh, S. Nagahama, N. Iwasa, T. Yamada, T. Matshushita, H. Kiyoku, Y. Sugimoto, T. Kozaki, H. Umemoto, M. Sano, and K. Chocho, "InGaN/GaN/AlGaN-based laser diodes with cleaved facets grown on GaN substrates," *Appl. Phys. Lett.*, **73** (6) 832-834 (1998).
6. J. Tominaga, F. Hiroshi, A. Sato, T. Nakano, T. Fukaya and N. Atoda, "The near-field super-resolution properties of an autimony thin film," Jpn. J. Appl. Phys. **37**, Part 2, No. 11 A, L323-L325 (1998).
7. D. G. Flagello, T. Milster, A. E. Rosenbluth, "Theory of high NA imaging in homogeneous thin films," JOSA A 13(1), pp. 53-64 (1996).

8. T. D. Milster, K. Shimura, J. S. Jo, K. Hirota, "Pupil-plane filtering for improved signal detection in an optical data storage system incorporating a solid immersion lens," *Opt. Lett.* 24(9), pp. 605-607 (1999).
9. K. Hirota, T. D. Milster, K. Shimura, Y. Zhang and J. S. Jo, " Near-field phase change recording using a GaP hemispherical lens," *Jpn. J. Appl. Phys.* 39(2000), Part 1, No. 2B, p. 968-972 (2000).
10. K. Kishima *et al.* "Near-field phase-change recording using a GaN laser diode," paper MC2 in Conference Digest of 2000 Optical Data Storage, 14-17 May, 2000, Whistler, British Columbia, Canada, sponsored by IEEE/Lasers and Electro-Optics Society, Piscataway, N. J., IEEE Catalog Nuber 00TH8491, pp. 33-35.
11. A. Partovi, D. Peale, M. Wuttig, C. A. Murray, G. Zydzik, L. Hopkins, K. Baldwin, W. S. Hobson, J. Wynn, J. Lopata, L. Dhar, R. Chichester, J. H. Yeh, "High power laser light source for near-field optics and its application to high-density optical data storage," *Appl. Phys. Lett.* **75** (11), 1515-1517 (1999).